

Executive Summary High-Yield Scenario Workshop Series Report

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ENERGY

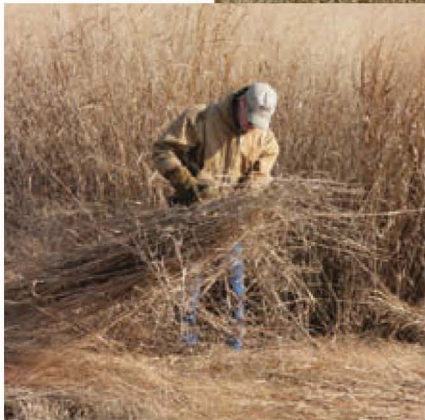
Energy Efficiency &
Renewable Energy



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FOREWORD

The “High-Yield Scenario” and why it is necessary

The 2005 Billion-Ton Study^a (BTS) estimates the amount of biomass resource that could potentially be available after other market demands for biomass resources are met. Preliminary assessments identified more than 1 billion tons of biomass available annually from agricultural residues, woody residues, and herbaceous and woody energy crops—a volume sufficient to help offset 30% of U.S. transportation fuel consumption.

The BTS relied on estimates of future production capability based on data and technology that were available at the time of the assessment. Since the release of the BTS, research efforts in both public and private sectors have contributed to a clearer understanding of the constraints and opportunities for establishing a sustainable, commodity-scale biomass market capable of supporting a bioenergy industry.

Some studies suggest that soil productivity limitations that reduce the amount of resource available under the current state of technology may be overcome, to an extent, with innovative tillage and cropping regimes. Others report that advancements in crop development and management suggest greater yield potential for some resources than those projected in the BTS assessment.

The “High-Yield Scenario” workshop series was sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (DOE/EERE) Biomass Program to identify and discuss the challenges associated with substantially increasing production of lignocellulosic biomass resources, such as agricultural crop residues (in particular, corn stover) and herbaceous and woody energy crops, to sustainably supply feedstock for biorefineries.

Workshop participants were selected from widely known and respected experts in diverse segments of industry, academia, and government. Individual workshops were held in St. Louis, Missouri, on December 3, 2009, and in Chicago, Illinois, on December 10 and 11, 2009.

A full report of the workshop discussions is available online.

^a Perlack RD, LL Wright, AF Turhollow, RL Graham, BJ Stokes, DC Erbach (2005) Biomass as a feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply, DOE/GO-102005-2135.

The High-Yield Scenario Workshop Series Report and Executive Summary were prepared for the U.S. DOE/EERE Biomass Program, by Idaho National Laboratory (INL).

Editors include Leslie Park Ovard, Thomas H. Ulrich, David J. Muth Jr., and J. Richard Hess from INL’s Biofuels and Renewable Energy Department; Steven R. Thomas from DOE’s Golden Field Office; and Bryce J. Stokes from Navarro Research and Engineering, Inc.

Documents can be accessed at www.inl.gov/bioenergy/hys

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“HIGH-YIELD SCENARIO” WORKSHOP SERIES

EXECUTIVE SUMMARY

Exploring the technical feasibility of high-yield biomass production

Developing a sustainable cellulosic bioenergy industry capable of meaningfully offsetting fossil fuel consumption presents a number of challenges for current production systems. While existing systems are effective at meeting present demands for food, feed, and fiber, the amount of biomass needed to support a bioenergy industry will require more efficient use of existing systems and development and implementation of new systems and practices to achieve significantly higher levels of biomass production than current baselines. The challenge requires several approaches, which include increasing crop yield and improving production and supply chain efficiencies.

The potential to increase yields of cellulosic biomass continues to be debated. This discussion can be divided into two realms: (1) the maximum yield potential technically possible through crop development and management advances, and (2) external influences (i.e., environmental sustainability requirements, land-use change, economics/markets, and policy) that will impact the amount of resource actually available for bioenergy production. Both lines of discussion are important for reliably estimating biomass resource potential, but without an understanding of the former, the influences of the latter cannot be modeled.

The “High-Yield Scenario” Workshop Series

To get a sense of the potential impact of research and development (R&D) on biomass resource availability, and to evaluate the feasibility of yields higher than baseline assumptions used for past assessments, an alternate “High-Yield Scenario” (HYS) concept was presented to industry experts at a series of workshops held in December 2009. The workshops explored potential future production of corn/agricultural crop residues, herbaceous energy crops (HECs), and woody energy crops (WECs).



Workshop Findings

1. For each category of biomass resource, experts from diverse backgrounds were optimistic that sufficient yield improvement could be achieved by 2030 to support a HYS.
2. Yield improvements are needed for all crops; no single crop can do it alone.



Workshop participants were asked to identify and consider issues that enable or constrain higher yields, providing referenceable justification wherever possible, and project future yield potential that could be achieved as advancements in technology and management strategies currently on the horizon are implemented and barriers addressed. Contextual discussions included influences of environmental sustainability requirements, land-use change, economics and markets, and policy, but projections assumed that these were adequately addressed to enable the maximum yield potential technically possible for biomass production.

Workshop-specific baselines, projections, technical barriers, and promising advances are summarized in this document. See the full report for detail about participants' and observers' workshop input regarding specific energy crop development issues and external influences (i.e., environmental sustainability requirements, land-use change, economics/markets, and policy) that will impact the quantity of cellulosic biomass available for bioenergy production.

Representation of Industry Expert Opinion

Widely known and respected experts were selected from diverse segments of industry, academia, and government. To assure the discussions explored each workshop topic systemically, participant panels included experts ranging from crop/plant breeders and geneticists to equipment manufacturers, specialists in environmental sustainability and economic viability, and feedstock producers.

The participants' diversity of expertise allowed workshop sponsors to assess the breadth of related issues that support or constrain efforts towards increased feedstock yields. This diversity also presented challenges for reaching coordinated consensus among participants when they were asked to estimate future yield potential and other specific yield-related values.

Workshop participant input is discussed in terms of trends and is intended to illustrate the variety of expert opinion that currently exists, provide some context for those opinions, and establish some industry-informed justification for model inputs for a HYS resource assessment case study.

Participants do not necessarily support all opinions appearing in this executive summary or in the full report, but their input is included within the ranges presented. Wherever possible, the full report references actual participant input (anonymously), including literature recommendations (see Notes and References section at the end of each workshop summary in the full report).

Assumptions Regarding Yield Improvement Projections

Participant discussions focused on identifying the crop and management developments needed, and those most likely to be realized, to produce a step-change in currently projected yield improvement rates. In many cases, the likelihood of these improvements being achieved depends on external influences including environmental sustainability requirements, land-use change, economics/markets, and policy. Participants were asked to make projections under the assumption that these external factors are favorable to support a HYS.

Corn/Agricultural Crop Residues

Sufficient historical data exists for the U.S. Department of Agriculture (USDA) to publish and regularly update projections for future corn production, which, in turn, can be used to project future stover residue production. The USDA projections available at the time of the workshops are shown in Table 1.

Table 1. Extrapolated USDA baseline projections for corn grain production for three future time periods (based on 2009 yield data).

	2009	2017	2022	2030
Corn yield (bu/ac)	157	174*	183*	201*

**2017 based on USDA 10-year baseline projections. 2022 and 2030 are straight extrapolation from baseline.*

Participants demonstrated clear agreement on continued growth of corn grain yields through 2050 (Figure 1). The greatest difference in participant opinion involves the rate of improvement. Figure 1 shows that a majority of participants (Camp 1) believed that genetic development and advanced management concepts would produce a near-term step change in annual yield increase (4% or greater) and enable grain yields approaching 250 bu/acre by 2030. As evidence, one participant reported very high yield levels using hybrids released just a few years ago (240–250 bu/acre) and 300+ bu/acre with their newest genotypes. This increase is supported by literature as well, with documented contest-winning grain yields of up to 360–370 bu/acre using seed hybrids available today.

The remaining participants (Camp 2) believed that advancements would continue at a rate more consistent with past yield improvement, and that it would be 2050 or later before HYS yields would be achieved (nearer to 2% annual increase and the USDA baseline).

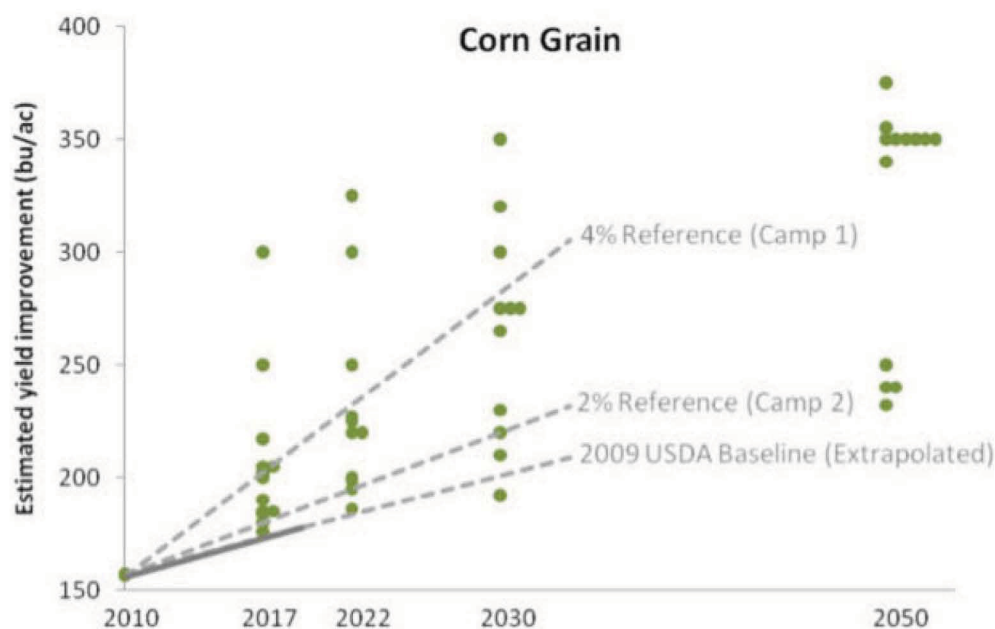


Figure 1. Projections for future corn yield fell into two camps: Camp 1 estimates the HYS is achievable by 2030 and Camp 2 believes it could be achieved around 2050 or later.

Workshop Participants (Corn/Agricultural Crop Residues)

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Todd Mathisen

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Michael C. Roth

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Lee Stromberg

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Three primary concepts emerged upon review of workshop presentations, participant comments, and supporting literature:

1. Harvest time HIs increase as grain yield increases
2. The material balance calculations needed for accurate stover availability analysis require HI at physiological maturity, for which less data exists to construct HI trend analysis
3. HI is a crop characteristic that can be engineered to serve market drivers as they emerge and change in a HYS.

Harvest Index (Ratio of Grain Mass to Total Aboveground Plant Mass)

Participant discussion about harvest index (HI) mirrored the challenges and complexities across the industrial and research communities. Information was presented on field studies demonstrating an increase in harvest index as the crop has undergone development for increased grain yield. It was also pointed out that HI is a crop characteristic that reflects market drivers. A number of participants entered the discussion with the opinion that HI will remain relatively stable, and though they did not come to a group consensus that HI will increase, many left questioning what impact future crop development would have on HI.

HI was primarily discussed as a harvest time measurement, which is worth exploring considering that the difference between HI at physiological maturity and harvest time may impact the HYS. When investigating HYS biomass availability, it is important to account for all biomass material that enters the system. Material lost between physiological maturity and harvest operations, while not harvestable, is still potentially available for soil maintenance and other ecosystem services.



Dedicated Energy Crops

Herbaceous and woody energy crops are in various stages of development, and there is generally little historical production data available from which to project future yield improvement. To estimate potential future yield improvements for herbaceous energy crops (HECs), participants first discussed the yields these crops are currently capable of achieving in various regions of the country. Participants then projected the rate of improvement (% annual increase) that could be achieved.

To estimate potential future yield improvements for woody energy crops (WECs), participants projected the rate of improvement from woody crop yields available in literature. For discussion management purposes, the dedicated energy crops were discussed by species in the applicable land resource regions shown in Figure 2.

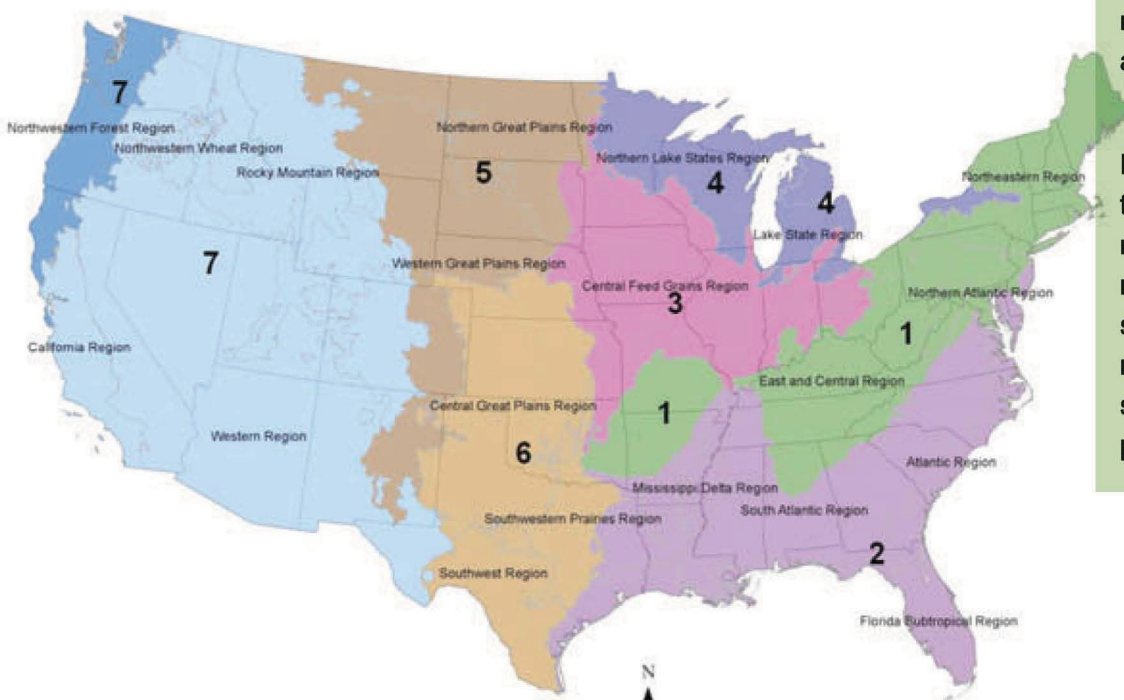


Figure 2. Land resource regions used to estimate current yields of HECs and WECs (adapted from USDA-NRCS [2006]).^b

Projecting Future Yields for Dedicated Energy Crops

Projecting the technically feasible future yield potential of dedicated energy crops is a complex process involving multiple species and varieties, varying yield averages by growing region, the various stages of crop development for each species, and a number of other factors.

For brevity in this summary, the projected improvements are indicated with nationwide averages and simple rates of improvement. (See full report for species-and region-specific projections.)

^bUSDA-NRCS (2006) Land Resource Regions and Major Land Resource Areas of the United States, the Caribbean, and the Pacific Rim, USDA Agriculture Handbook 296.

Workshop Participants (Herbaceous Energy Crops)

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Herbaceous Energy Crops (HECs)

Participants discussed currently achievable yields for switchgrass, miscanthus, mixed perennial grasses, energycane, and sorghum, which are shown in Table 2.

Table 2. Currently achievable HEC yields agreed upon by participants.

	Switchgrass	Miscanthus	Mixed Grasses	Energycane	Sorghum
Dry ton/ac/yr	5–6	10–12	5–6	10–14	8–9

Ranges span the most frequent estimates [mode] for multiple land resource regions [Figure 2]—see full report for region-specific yield information.

Following discussion of limiting factors and likely advancements that could enable the HYS, participants projected potential yield improvements (%) achievable by 2017, 2022, 2030, and 2050 for each species. Figure 3 shows the distribution of their individual projections by region. Reference lines indicate annual yield improvements of 1% as an assumed baseline rate of improvement (gray solid line) and 2 and 4% (gray dashed lines), which may be achievable as more effort and funding are applied to accelerate progress.

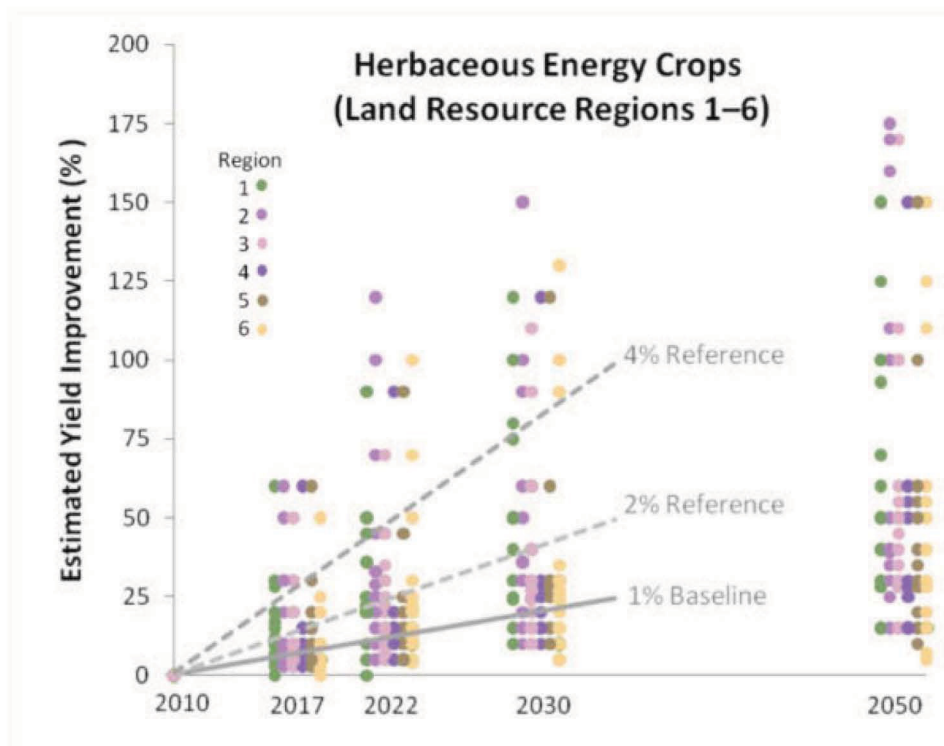


Figure 3. The greatest density of projections for HECs, collectively, occurs at improvement rates between ~0.5 and 3% in the near term, and there is optimism for some species to experience even greater rates of improvement in some regions. Optimism for rapid increase of rate improvement (2% and greater) was projected in Regions 1, 2, 3, and 6.

Woody Energy Crops (WECs)

Currently achievable yields for poplar, willow, pine, and eucalyptus were established from literature as a composite across multiple site studies (Table 3).

Table 3. Currently achievable WEC yields.^c

Species	Poplar	Willow	Pine	Eucalyptus
Dry ton/ac/yr	3.5–6.0	5.1	3.5–5.5	5.5–6.0

(Ranges span multiple land use resources [Figure 2]—see full report for region-specific yield information).

Following discussion of limiting factors and likely advancements that could enable the HYS, participants projected potential yield improvements (%) achievable by 2017, 2022, 2030, and 2050. Figure 4 shows the distribution of their individual projections by region. Reference lines indicate annual yield improvements of 1% as an assumed baseline rate of improvement (gray solid line) and 2 and 4% (gray dashed lines), which may be achievable as technical barriers are overcome.

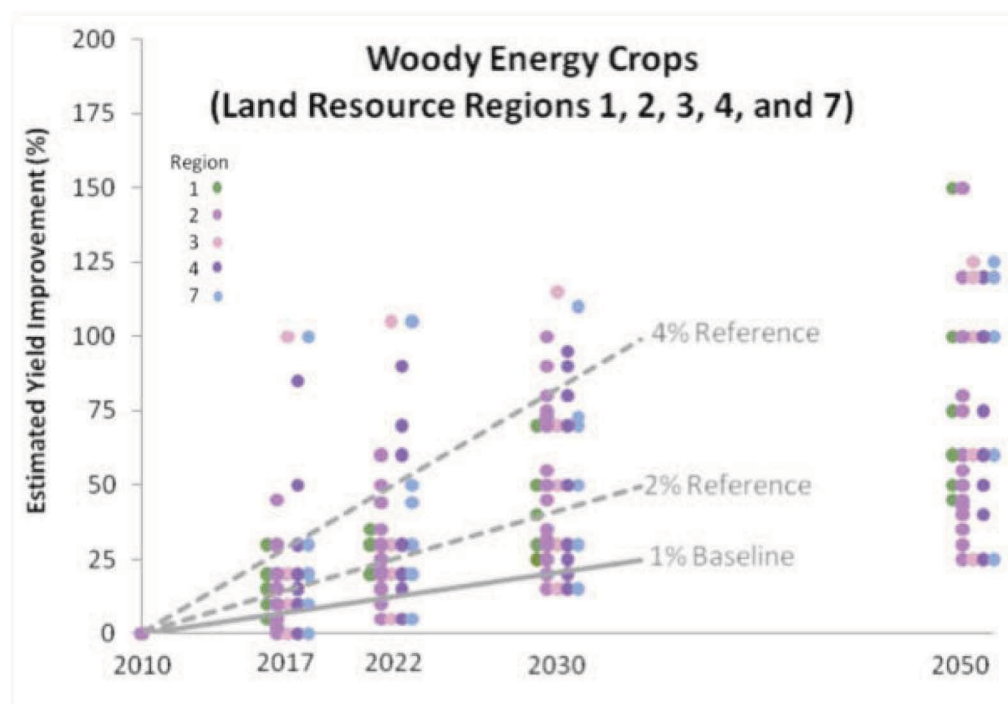


Figure 4. The greatest density of projections for WECs, collectively, occurs at improvement rates between ~1 and 4% in the near term, and there is optimism for some species to experience even greater rates of improvement in some regions. Optimism for rapid increase of rate improvement (2% and greater) was projected in Regions 1, 2, 4, and 7.

Figures 3 and 4 illustrate that industry experts believe that HECs and WECs produced using the most appropriate varieties in the most appropriate growing regions are technically capable of achieving greater than a 1% baseline yield improvement, and they are likely to do so as policies and markets drive advancements in crop development and management practices.

^c Wright, LL. 2010 submitted. Short Rotation Wood Energy Crops: History of Development and Current Status. Oak Ridge National Laboratory, 2010 (forthcoming).

Workshop Participants (Woody Energy Crops)

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Tim Volk

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Research Plant Geneticist, USDA-FS



Corn Stover

Corn stover (the stalks, leaves, and cobs that remain after the corn grain is harvested) is an important resource for renewable energy production because of its abundance and high cellulose and hemicellulose content. Corn stover currently provides 75% of total annual crop residues available for biofuel production, with approximately 5.1 million acres producing an estimated 180 million tons of total residue.

(Photo courtesy of Iowa State University)



Switchgrass

Switchgrass is a native warm-season perennial grass that can thrive in a variety of climatic conditions, growing seasons, soil types, and land classes. It can be grown on land that is not suitable for row crop production in either conventional tillage or no-till production systems.

(Photo courtesy of David Bransby, Auburn University)

TECHNICAL BARRIERS

Technical barriers to achieving sustainable increased yields of the crops discussed in the HYS workshop series fell into three general areas: exploiting species yield potential, improving tolerance to stressors, and innovative management strategies to support both. Some of the issues of greatest impact to technical feasibility are included in this summary; see the full report for further discussion related to technical feasibility of increased yield and secondary influences related to environmental sustainability, economic viability, land-use change, and other technology and policy-related barriers and opportunities.

Corn/Agricultural Crop Residues

Of the 1.3 billion dry tons of biomass resource that the United States is estimated to be capable of producing annually within 35 to 40 years, Perlack et al. (2005)^a estimated 170 to 256 million dry tons would come from corn stover. Since that assessment, the amount of stover potentially available has been reconsidered to accommodate the amount of biomass that needs to remain in the field to maintain soil productivity and other sustainability requirements.

Participants identified technical barriers that challenge high-yield production of corn stover and ranked them according to greatest impact on achieving sustainable increased average annual yields (Table 4).

Table 4. Technical barriers of greatest impact to HYS corn stover production.

Corn Stover-Specific Technical Barriers

1. Tolerance to drought, pest, and other stress factors that increase yield variability
2. Genetics
3. Changing global weather patterns
4. Nutrient-use efficiency
5. Soil productivity
6. Changing pests spectrum
7. Rate of return on investment
8. Physiological limitations of higher plant densities
9. Rotation crop selection

A number of participants were optimistic that there is still opportunity for stover yield improvements within the ultimate potential of corn and recommended continued work in genetics, including selective breeding and the application of new biotechnology approaches. It was stressed, however, that without a market pull for higher stover yields relative to grain yields, the emphasis will continue towards maximizing grain yields.

Significant opportunities for yield improvement lie in improving plant tolerance to stressors. Yield increases are expected as a result of reducing variability in corn yield and selecting hybrids that push the physiological limits of higher plant densities. Application of biotechnology can successfully improve plant tolerance to stressors and solve problems, such as the solution developed for infestation by corn root worm and the European corn borer, two of corn's most detrimental insect pests. Resistance to fungal disease is

also expected to improve yields with the exploitation of genetic diversity and the continued application of molecular plant breeding.

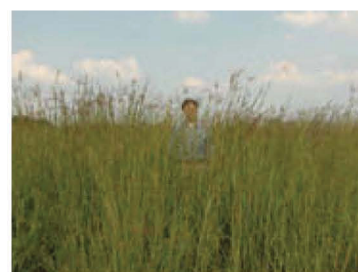
There may be significant potential for yield gains through innovations in management to produce the best growing conditions possible for the species, growing region, and land class. One participant noted that in high-yield contests, where everyone has access to the same seed varieties, yield still varies, suggesting that “the major difference between average yields and yield contest yields is management.” Innovative tillage and other soil management practices, including development, validation, and extension of best management practices will also support the HYS.

Herbaceous Energy Crops

Herbaceous energy crops (HECs) are important for long-term sustainability of developing biofuels and bioenergy industries. HECs are generally fast-growing, high-yielding varieties of grassy biomass crops that have broad adaptability to growing conditions and land classes and can be incorporated into conventional farming operations. Some of the HECs under consideration for bioenergy production in the United States are *Panicum virgatum* (switchgrass), mixed perennial grasses, *Saccharum* (energycane), *Miscanthus*, and *Sorghum*. These crops are at various stages of genetic and agronomic development, and a great deal of work can still be done to improve their agronomic performance and relative acceptability of each to producers and biorefiners in a commodity-scale biomass market. Participants’ discussion of technical barriers for high-yield production of HECs consistently reflected its status as a fledgling resource for which there is little historical data and very few existing markets to support development (Table 5).

Table 5. Technical barriers of greatest impact to HYS HEC production.

HEC-Specific Technical Barriers
1. Limited background research into the agronomy, breeding systems, and environmental sustainability of these crops, relative to our major feed/food crops
2. Lack of existing markets for all bioenergy crops
3. Limited producer experience with HEC production systems
4. Lack of field-scale understanding of nutrient amendment needs for HEC crops
5. Unreliable establishment success
6. Slow pace of genetic improvement
7. Lack of herbicide labeling for HEC species and their effects on yield
8. Producer risk tolerance
9. Lack of comprehensive research on mixed perennial grasses (switchgrass has been the focus)
10. Lack of genomic resources and genome understanding



Mixed Perennial Grasses

Mixed perennial grasses (Big Bluestem shown in image) refer to diverse mixtures of native perennial grasses. Some studies indicate that mixtures of prairie grass planted on degraded agricultural land can produce more bioenergy than the same land planted with various single species. Other work suggests that monocultures or mixtures work best if managed at a higher level.

(Photo courtesy of Ernst Conservation Seeds)



Energycane

Energycane refers to sugarcane hybrids that are high in fiber and low in sugar. It is a tropical perennial grass that can be grown in the southern United States and in field trials has outperformed sugarcane in drought conditions, on marginal land, in cooler environments, and with fewer inputs.

(Photo courtesy of Ed Richard, USDA-ARS)



Miscanthus

Miscanthus is a tall perennial grass that is easy to grow, requires few inputs—particularly low nitrogen—and relatively little water, and produces a feedstock with low water content (15% typically at harvest) and ash content. Miscanthus can be grown on lands not suitable for row-crop production, producing a strong cane-like stem, and recapturing most of its nutrients underground at year-end before the harvest.

(Photo courtesy of Mendel Biotechnology)



Sorghum

In many areas of the United States, high-biomass sorghum can be produced as a quick-growing annual. High-biomass sorghum uses water and inputs efficiently, has robust establishment characteristics, and can be produced on lands considered marginal for other crops.

(Photo courtesy of Blair Fannin, Texas AgriLife Research)

Some of the most immediate needs for assessing increasing HEC yields are in basic agronomic research, field-scale trials, and crop development.

1. Conduct agronomic research on seed rate, planting time, harvest time, etc.

Continued agronomic research of energy crops will help identify important sustainability and nutrient management issues. One method to address both issues is through the integration of a cover crop (such as legumes) to a feedstock production system, which improves soil productivity while potentially reducing nitrogen application requirements.

2. Perform wider geographical side-by-side trials for statistically valid comparisons

Yield trials using best-in-class varieties should be conducted on land intended for energy crop growth on a regional basis as well as small plots. Larger scale field trials are needed as well as long-term trials to determine if the land is capable of producing consistent yields over time. These trials would result in determining yield capability across different landscapes and identification of higher yielding energy crops on a regional scale. This provides an opportunity to determine the optimal mix of energy crops, soil and water conservation efforts, and wildlife diversity locally and regionally. Improved genetics could also increase regional diversity of energy crops, which would help mitigate risks for producers and biorefineries.

A general lack of knowledge of regional characteristics, such as landscape and weather, makes it difficult to determine production capabilities of different regions. Development of best management practices per crop by region should be completed to determine sustainable removal rates while optimizing extractable energy per acre.

3. Develop and implement long-term systematic crop improvement programs for each crop

Another enabler is the establishment of long-term systematic improvement programs for each crop. This includes the development of a government-sponsored R&D program where academic laboratories and government agencies develop genetic resources and collaborate with industry to produce enhanced crop varieties. One method of enhancement is through heterosis, which might produce very large yield improvements in switchgrass, *Miscanthus*, and energycane. Another promising method for yield improvement is through site- and timing-specific nutrient amendment and the use of feeder crops, such as N-fixing legumes.

Woody Energy Crops

Woody energy crops (WECs) are usually referred to as purpose-grown plantations in which the bolewood, probably the bark, and much of the limbs and tops are used as feedstocks for energy. They can also be referred to as short-rotation woody crops (SRWCs). Currently, SRWCs are grown primarily to use the bolewood for pulpwood and, in some limited cases, for lumber. In the general sense, energy crops and SRWCs are intensively managed, fast-growing species that produce large amounts of wood and woody biomass over a short period of time, usually less than 10 years. Depending on the species and the production method, the rotation length can be shortened for purpose-grown energy crops to as little as 2 years when coppiced (clumped trees or shrubs resprouted from stumps), but typically are 5 to 12 years when grown as single trees from cuttings or seedlings. For coppiced stands, after 3 to 7 harvest cycles, the stumps are removed or killed and replaced with new, improved-quality stock.

Some of the woody energy crops under consideration for bioenergy production in the United States are *Populus* (poplar), *Salix* (willow), *Pinus*, (pine), and *Eucalyptus* hybrids. These species have had significant research investment in improving yield from genetic breeding and/or biotechnology, nutrition management, and competition control; however, more effort has gone into growing high-quality trees for pulpwood and other higher-value products, and less effort has gone into maximizing total biomass yields. As the focus has turned back to energy, WECs are being further developed with different rotation lengths and a mixture of plantings and coppicing in the same plantation to maximize production and reduce costs over various harvest cycles. Participants identified specific research needs to accelerate development of WECs for energy feedstocks (Table 6).

Table 6. Technical needs of greatest impact to HYS WEC production.

WEC-Specific Technical Barriers
1. New and improved varieties, lines, families – molecular genetics and breeding methods
2. Fertilization and soil management
3. Silvicultural prescriptions/regimes backed up by “business cases” and “how-to” guidelines for landowners
4. Production and testing of elite clones with enhanced candidate gene activity
5. Application of precision agriculture and forestry management
6. Fundamental understanding of the genetics driving yield improvement
7. Better understanding of cost structures and benefits
8. Integrated research (balanced between basic and applied) programs
9. Better identification of all products in the biomass
10. Enhanced drought and frost tolerance, disease and pest resistance.

Participants’ highest ranked suggestions for future R&D needs, based on impact to support HYS production of WECs, are as follows:

1. Pursue molecular genetics and transgenics to develop new and improved varieties, lines, and families

Promising crop development research objectives to support the HYS include testing families already developed to expedite release of new varieties and expand the number of species and hybrid clones being developed, development of varieties with better nutrient-use efficiency and drought and frost tolerance, development of varieties with natural pest and disease resistance, and development of advanced-generation pedigrees and establishment of large association studies to identify candidate genes controlling desired traits. Research on transgenic clones is needed to identify and confirm which genes control yield, particularly for all WEC species.



Poplar

Poplar is native to most of the Northern Hemisphere and includes 25–35 species. For energy crops, we usually refer to the use of interspecific hybrid poplars (e.g., crosses between cottonwoods), has been as these are the ones genetically improved through breeding for enhanced production, which can exceed 15 dry tons/ac/yr in the Pacific Northwest. They are expected to be grown on agricultural cropland and have a wide geographic range depending on the species and water availability. Poplars grow fairly well in the northern, central, and southern United States. Extensive genomic resources, ease of clonal propagation and transformation, will allow the generation of advanced transgenic clones with enhanced traits.

(Photo courtesy of Ron Zalesny, USDA-FS)



Willow

Shrub willows have several characteristics that make them an attractive energy feedstock: (1) high yield on 3–4-year rotations, (2) ease of propagation from cuttings, (3) broad genetic base, (4) excellent coppicing ability, and (5) the same energy content as other woody species. Willow grows best in well-drained to poorly drained soils in the northeast, Midwest, and mid-Atlantic regions.

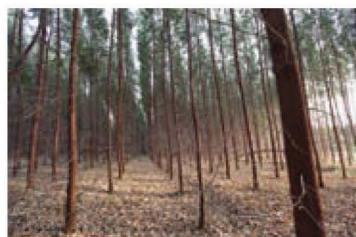
(Photo courtesy of CNH America, LLC)



Southern Pine

Currently, southern pines (primarily Loblolly and Slash Pine [Slash Pine shown in image]) are being grown for sawtimber and pulpwood, but they have great potential as an energy crop or in management regimes that produce biomass and other products. These species grow well across a large portion of the southern United States, on many soil types and levels of moisture, and have been used to reforest many acres of depleted farm land.

(Photo courtesy of David South, Auburn University)



Eucalyptus

Eucalyptus is the world's most widely planted hardwood species. Its fast, uniform growth, self pruning, and ability to coppice make it a desirable species for timber, pulpwood, and bioenergy feedstocks.

(Photo courtesy of Cargill Inc., © 2010 Cargill Incorporated / P. Chandramohan)

2. Research and develop management strategies and technology advances to support increased yields

Large field trials are needed with herbicides and fertilizers to maximize plant production, plant spacing/density and other silviculture requirements specifically for bioenergy crop production and coppice management. Site-specific, integrated management schemes need to be developed. Intercropping studies show particular promise in supporting increased yields and can increase more natural nitrogen capture and release to SRWCs, capture growth potential during early years of SRWC establishment, or integrate a high-value crop (e.g., saw logs) with an energy crop.

Large, long-term fertilization and soil management studies are needed to better understand the balance between nutrient inputs, removals, movement, fixation, and availability, particularly on marginal lands. Impacts on the ecosystem, including competing plants, should be part of this analysis.

3. Bridge research gaps between genetic breeding and applied programs and integrate research programs

Basic and applied research programs should be integrated to support a holistic, systems-based research approach. Analysis of interdependent issues, such as nutrient management, spacing, rotation length, pest and disease management, soil loss, and weed management will help research identify the elements of greatest impact to the overall system. The integrated research portfolio should include short-term applied objectives balanced with longer term (7–8 years) basic work, including genetics, silviculture, and harvesting.

Participants suggested that large-scale, multi-site yield trials performed over multiple rotations are also needed to examine potential growth of species and performance under a variety of growing conditions. These studies need to cover a range of soils and climate conditions. Methods and tools for making informed decisions on where to test and deploy genotypes are needed to help increase plantation success and ultimate yield.

“HIGH-YIELD SCENARIO” WORKSHOP SERIES FULL REPORT

The “*High-Yield Scenario*” *Workshop Series* full report presents the substance of the facilitated discussions, participant panel input captured by the idea/discussion management tool and workshop facilitators, and observer input captured by the workshop rapporteur.

The workshop series input identified critical topics in crop species development, markets, policies, and other related issues of impact to development of a bioenergy industry. There was not always time to satisfactorily explore these issues, and workshop sponsors acknowledge that these are important and complex topics that will be explored in greater depth as research goes forth.

Full report is available at www.inl.gov/bioenergy/hys

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**“High-Yield Scenario” Workshop
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